# A SURVEY OF POTENTIAL APPLICATIONS OF FLUIDICS TO SPACECRAFT ATTITUDE CONTROL

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Presented at the SAE Committee A-6 Symposium on Fluidics



San Francisco, California
October 21, 1966



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# ABSTRACT

A study has been made to determine the feasibility of incorporating fluidic components or subsystems in a space probe vehicle attitude control system. The Lunar Orbiter vehicle attitude control system specifications have been used as a general basis for system analysis. The attitude control is analyzed on a block diagram basis, the function and present design of each block being briefly described. Suggested schemes for fluidic implementation of each block are discussed and comparisons of the two approaches are made in terms of relative power consumption weight and reliability.

Although a complete fluidic attitude control system does not appear feasible within the present state of the art, several areas may well profit by conversion to fluidic hardware. Prime areas for fluidics appear to be thrust vector control and the inertial reference unit, while the fluid power supply and electronic-to-fluidic interfaces are major problem areas.


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## INTRODUCTION

The recent resurgence of interest in fluid operated instrumentation, and especially in the newer "pure fluid" devices which avoid moving parts, promises great improvements in many fields of control and data handling. In some cases these improvements are already being realized, and in other cases obvious advances appear to wait only for the development of suitable hardware. The potential for fluidic devices in spacecraft control systems is not, however, so clear-cut.

The primary goals that a space vehicle designer must consider are low system weight and high system reliability in the face of such serious space hazards as high radiation levels, a wide range of temperature variations and extreme vacuum. Suggestions for applying fluidics to spacecraft systems have generally been centered on attempts to take advantage of the high tolerance of these devices to extreme temperature and radiation environments and on their inherent ruggedness and reliability. The necessary presence on board the space vehicle of the telemeter system with its complex array of vulnerable electronic components tends to negate much of the advantage which might otherwise be realized from the high environmental tolerance of a fluidic attitude control system. Other obvious problems include size, weight and power requirements of a fluidic system and the necessity for its integration with certain electronic components which, at this time, have no fluidic equivalents.

The purpose of this paper is not to present any original work or concepts, but simply to examine the design requirements of a typical spacecraft attitude control system in the light of current fluidic technology in order to

determine which, if any, of the engineering problems involved might profitably be solved by fluidics. Because of recent intimate experience with the developmental problems of the Lunar Orbiter attitude control system, this vehicle has been chosen as a working example and this paper deals exclusively with the problems of the fully stabilized deep space probe of the Lunar Orbiter class.

In this paper the term "fluidics" is used to denote, primarily, no-moving-parts, jet interaction devices, but, in some cases it is used in its broader sense to include hybrid devices employing moving parts where these appear to offer the best solution to a particular problem.

## SAMPLE SYSTEM

The general attitude control philosophy used by the Lunar Orbiter is typical of most current space probe vehicles. A "cruise attitude" is maintained whenever possible, using body-fixed sun sensors for attitude reference about the pitch and yaw axes and a body fixed star sensor for roll reference. When the vehicle must be temporarily maneuvered to some other attitude for velocity adjustment or for the aiming of an experiment, three integrating rate gyros are used as references during the time of the maneuver, taking their initial conditions from the cruise attitude. In this way simple, drift-free attitude references can be used during most of the mission and the gyros are required to maintain their attitude "memories" for short periods only.

A set of small, cold gas reaction jets are used to provide control torques during the entire mission except during the time when the main thruster is in operation. At this time thrust misalignments and CG

uncertainties add up to disturbance torques which are orders of magnitude greater than can be handled by the cold gas jets. In the case of the Lunar Orbiter, the high control torques required are obtained by mounting the main thruster on a servoed gimbal system (Thrust Vector Control).

Figure 1 shows the general layout of the vehicle, pointing out the location of the major components of the attitude control system. Figures 2 and 3 show simplified block diagrams of the three control channels. As can be seen, the roll channel differs from the pitch and yaw channels principally in that no thrust vector control is required. Control loops required for the orientation and stabilization of the photographic experiment have been omitted in the interests of generality.

With the block diagrams as a guide, the following components were selected for a detailed examination:

1. Programmer
2. Control Amplifiers
3. Radiation Sensors
4. Inertial Reference Unit
5. Jet Valves
6. Thrust Vector Control
7. Power Supply
8. Interface Transducers

## PROGRAMMER

The programmer contains the logic needed to convert commands received by the telemeter to the detailed sequence of control events required to carry-

out each command. Verification of commands and storage of commands for future execution are also duties of the programmer. It requires the same selection of components as would a typical digital computer. Simple fluidic digital computers have been built, and there appear to be no basic problems in the construction of more elaborate units. Packaging densities of several hundred components per cubic inch are well within the state of the art when etched metallic fabrication processes are employed, and, since a "fluidic component" generally represents an entire amplifier or logic element, it should not be too difficult to meet size and weight requirements. The recent development of fluidic non-volatile memory elements (Ref. 1) could do much to reduce the power requirements and improve the reliability of such a unit. Operating speeds would, of course, be much lower than those of present electronic programmers, but should be entirely adequate for this application.

## CONTROL AMPLIFIERS

Logic devices and analog amplifiers are required for the various control loops of the attitude control system and the same remarks made about the programmer are applicable here. The choice of fluidic or electronic amplifiers would probably be dictated solely by the convenience of interface with the associated sensors and output devices.

## RADIATION SENSORS

The only absolute attitude references available to the deep space probe are celestial sightings. This means that any space craft attitude control system considered must contain some form of radiation sensors.

The sun is generally the brightest object in the spacecraft's field of view, and therefore the easiest to locate, and, since the orientation of the

spacecraft with respect to the sun is generally very important because of power supply and temperature control considerations, the sun is normally used for reference about two vehicle axes. For simplicity, body fixed sun sensors are used. These are so positioned on the vehicle that when they are pointing directly at the sun the vehicle is in its "cruise attitude" with its solar power collector normal to the sun line. Because of the relative brightness of the sun, the sun sensors can have a very wide angle of view and the spacecraft can "see" the sun and home it on it from almost any arbitrary attitude.

Because of the high level of radiation received from the sun, the development of a fluidic sun sensor does not present any great problem. Direct heating of a fluid by the sun's radiation is one approach.

Figure 4a shows such a device investigated at Langley. It consists of a simple "greenhouse" in which the sun's energy raises the temperature of the working fluid, changing both its specific volume and its flow characteristics. An assembly of two of these fluidic thermal detectors with a conventional analog amplifier, suitable flow restrictors and a sun shade as shown in Figure 4b provides a differential pressure signal proportional to pointing error in the same way that shaded photo cells give an equivalent electrical signal in present spacecraft systems. No attempt was made to optimize the design of this sensor and the sensitivity was quite low.

Another fluidic sun sensor studied at Langley is shown in Figure 5. In this case the thermal expansion of metal strips drives a conventional pneumatic pickoff by way of a flexible-leaf motion amplifying device. The heat sensitive elements consist of three-layer sandwiches; the outer layers are metal with a high coefficient of thermal expansion while the center layer is of thermal insulating material. The bending moment produced in the sandwich by

the front-to-back temperature gradient supplies the steady state component of the pointing error signal. The time lag made up of the thermal resistance of the insulating core and the thermal inertia of the back layer of metal supplies the phase lead component necessary for stabilizing the attitude control loop. The flexible-leaf motion amplifying device serves the dual purpose of improving the sensitivity of the sensor and providing a very high common-mode rejection characteristic, so that the performance of the device is fairly independent of ambient conditions.

A second reference point in space is needed to determine the vehicle's attitude about the sun line. The Lunar Orbiter uses the star Canopus for this point because of its brightness and advantageous position. (The direction of Canopus is nearly at right angles to the sun line.) Since there are so many stars and their individual brightness is many orders of magnitude less than that of the sun, the star tracker must have a very narrow field of view and must contain a very sensitive radiation sensor.

Because of the high sensitivities required, the outlook for an all-fluidic Star Tracker is not too encouraging. The Golay cell (Reference 2) appears to be the only fluidic radiation sensor in current use which might approach the required sensitivity. An N.E.P.*of $3.3\times10^{-10}$ watts has been attained (Reference 3) and the spectral response is very uniform. (A detector of this sensitivity would require a telescope aperture of about ten inches to attain a signal-to-noise ratio of one from Canopus.) In its present form the Golay cell employs an elaborate photo-electrical pickoff to convert the minute pressure pulses from its radiation sensitive fluid cell into electrical signals. Considerable developmental effort would be required to convert the Golay cell

* Noise Equivalent Power

into an all fluid instrument, and its sensitivity would have to be increased by nearly two orders of magnitude for practical use in a star tracker.

## INERTIAL REFERENCE UNIT

The inertial reference unit (IRU) is required to give the vehicle the capability of maneuvering away from its cruise attitude and of maintaining other arbitrary attitudes for short periods of time. In the case of the Lunar Orbiter it is also needed as a temporary cruise attitude reference during the times when the normal celestial references are occulted by the moon.

Integrating rate gyros have been used as attitude references in the inertial reference units of Lunar Orbiter, Ranger, and Mariner. Since these gyros have an angular range of only a few degrees, maneuvers are made, in the case of Ranger and Mariner, by switching the attitude control system to the gyro references and applying calibrated precessional torques to the appropriate gyros one at a time. The attitude control system then causes the vehicle to follow the gyro reference to the desired attitude. In the case of the Lunar Orbiter, the gyro is switched to its rate mode of operation, the vehicle is given a small angular rate about the maneuvering axis and the output of the gyro is integrated digitally to determine when the desired angle has been traversed. When the vehicle has reached the desired attitude, all three gyros operate in their integrating mode to provide three axes of attitude reference during this "inertial hold" phase of the mission.

It should be emphasized that the vehicle depends upon the gyros for attitude reference for short periods of time only, and that the gyros take their initial conditions from the celestial references at the beginning of each of these periods. This means that the gyros are required to have low, but

not excessively low drift rates. Something in the order of one degree per hour is sufficient for current missions.

The gyros have been one of the most troublesome areas in the spacecraft control picture. The vast number of precise and exotic operations required in the manufacturing process make each unit an individual work of art. Presently used integrating rate gyros with their flotation fluid and numerous heat sensitive parts are almost impossible to sterilize adequately for planetary landing missions. Although most faults can be detected by thorough preflight inspection, the incidence of these faults has been discouragingly high.

The substitution of vortex rate sensors and fluidic integrators for presently used integrating rate gyros offers an attractive possibility for avoiding the mechanical complexity and high speed moving parts of the gyros. Figure 6 shows a block diagram of such an attitude reference system. The early state of development of these instruments leaves considerable doubt as to whether suitable requirements for rate threshold and drift rate could be met in a small, low powered unit.

A less radical application of fluid technology to the gyro problem is in the use of gas lubricated bearings in more conventional gyro designs. The development of self generating gas bearings for conventional integrating rate gyros and for two axis free rotor gyros has been underway for a number of years. At least one of these developments has proved its long life and reliability by years of standby operation in ICBM service. So far, gas bearing gyros have not found a place in space probe control systems.

Figure 7 shows an unusually simple gyro design now being studied by contract at Langley for spacecraft applications (Reference 4). It is of the

free, or two axis type in which a single externally pressurized spherical gas bearing serves for both gimbal and spin bearings. The rotor is driven by gas pressure,and fluidic torquers and pickoffs are provided. Previous experience by the contractor indicates that the required drift rates can be met and the mechanical simplicity of design and freedom from temperature control and heat dissipation requirements should avoid many of the problems encountered with current integrating rate gyros. Since the free gyro provides attitude information about two axes, only two of these units will be needed in the inertial reference unit.

## JET VALVES

With the exception of the times during which velocity corrections are being made, the control torques required by the vehicle are extremely small, and are supplied by a set of cold gas reaction jets controlled by simple on-off solenoid valves. With a well designed system in limit cycle operation the gas consumption is very low, (the Mariner used about two pounds of gas during its trip to Venus), and the more complex internal momentum exchange systems using flywheels or gyros have not been competitive from a standpoint of weight and reliability for the type of missions presently being flown.

Although it may be possible to design a pure fluid valve which will cut off even when exhausting to a hard vacuum, it is unlikely that the leakage of such a valve can be reduced to a practical value. It would seem that the best approach to a fluidic reaction jet valve would be a mechanical, positive-sealing valve actuated by a diaphragm or piston. Figure 8 shows a conceptual sketch of such a valve. The time constant of this valve could probably be made somewhat less than its solenoid equivalent, but there does not appear to be any other advantage in this design other than its compatability

with a fluidic control amplifier.

## THRUST VECTOR CONTROL

At several points in a deep space mission, velocity changes of some magnitude must be made. Examples are midcourse corrections, orbit injection, orbit transfers, etc. This function is normally taken care of by a small, liquid-fuel rocket motor. The Lunar Orbiter uses a motor with a thrust in the order of one hundred pounds. With this magnitude of force, the smallest shifts in center of gravity and thrust vector alignment are going to result in appreciable disturbance torques on the vehicle. These torques are of a much greater magnitude than can be corrected by the small cold gas attitude control jets, so some provision must be made for generating high control torques about the two vehicle axes effected during the time velocity adjustments are being made by the large thruster. The generation of these high control torques in a reasonably simple manner has proved one of the stickiest problems in the attitude control design. Ranger and Mariner used jet vanes in the thruster nozzle, positioned by directly coupled DC torque motors of alarmingly low torque capability. In the interests of simplicity, the original Lunar Orbiter design called for auxiliary high-thrust cold gas control jets mounted at the tips of the solar panels. High gas consumption and stability problems forced a design change to gimbal mounting of the rocket motor. The gimbal is servoed about the two control axes by fairly conventional DC servo motors.

Each of these systems is workable but each has definite disadvantages. For example, the gimbal-thruster arrangement of the Lunar Orbiter involves the added weight and complexity of the gimbals, flexible fuel and oxidizer

lines on the thruster, and the servos themselves, each containing a dc motor, gear train, lead screw, potentiometer and an amplifier - a total of sixteen major moving parts.

A fluidic secondary injection thrust vector control (TVC) would appear to be a "natural" for this application and should result in a considerable savings in weight and improvement in reliability even if it were the only fluidic device in the attitude control system.

A number of approaches have been made to the problem of secondary injection TVC using pure fluid valves. (Ref. 5, 6, 7, 8). Figure 9 shows a rudimentary layout of such a system using a pair of proportional or monostable fluid amplifiers to control the flow of gas from the thruster combustion changer to the secondary injection ports. Since these are constant flow amplifiers, the gas not directed to the secondary injection ports is expanded through small auxiliary nozzles to conserve overall specific impulse. With this arrangement the thruster can be rigidly attached to the vehicle, all moving parts are eliminated, and such troublesome items as motor commutators and feedback potentiometers are not required. An appreciable reduction in the weight of the mechanical components should be realized, but this would be offset to some degree by the extra fuel needed for the secondary injection system. At this time most of the effort on secondary injection TVC has been directed toward the large booster motors, and little interest has been shown in fluidic secondary injection for the small velocity control thrusters suitable for space probes. The development of suitable fluid amplifiers and their integration into the already critical design parameters of these small thrusters would require considerable developmental effort, but the resulting

package could well represent fluidics' most valuable contribution to deep space probe engineering.

## POWER SUPPLY

A common problem for fluidic devices used in a space probe is the source of power. Of the devices discussed, only the TVC requires the expenditure of large quantities of gas at a fairly high pressure, and this for short periods of time only. This demand must be met either by stored cold gas, by a suitable hot gas generator, or by tapping the thruster's combustion chamber. The other devices and systems discussed will, in general, operate continuously throughout the mission, so that a closed, recirculating gas system would be necessary.

The most straightforward approach would be the use of a mechanical gas pump powered by the vehicle's electrical system. A centrifugal gas pump directly connected to a brushless DC motor and equipped with gas lubricated bearings would represent a good combination of efficiency and reliability. An overall efficiency as high as 70% might be realized with careful design.

Published figures on the Ranger solar power supply (Reference 9) show recovery of about 8 watts of electrical power per square foot of solar panel. Since, at earth's distance, about 130 watts of solar energy per square foot are available (Reference 10), the proposition of direct conversion of solar energy into fluid power may be attractive where a considerable amount of fluid power is required.

Work has been done on solar energy versions of the Brayton gas cycle and the Rankine liquid-vapor cycle as sources of fluid power for turbogenerator systems for space vehicles (Reference 11). For the relatively

high powered systems studied (30-100 KW) the weight of the fluid power supply was about an order of magnitude less than that of the equivalent solar cell supply. This weight advantage would probably be reduced in the smaller power supplies required for a Lunar Orbiter class space probe system, but weight savings in the power supply alone could be a strong motivation for considering an all-fluidic control system.

Temporary storage of energy for operation during maneuvers and when the sun is occulted could be provided by the heat of fusion of LiH or a similar substance at a watt-hour-per-pound rate at least as high as presently used storage batteries can give. (Reference 11).

Figure 10 shows a block diagram of a Rankine cycle fluid power supply. The fluid is vaporized by solar energy, the vapor drives the fluidic devices and is condensed to a liquid by radiation. The liquid is then returned to the vaporizer by a pump to repeat the cycle. The pump is the only component requiring moving parts, and there appear to be some good possibilities for avoiding these. No-moving-parts pumps employing capillary forces and osmosis have been considered (Reference 12) and the historic boiler injector (Reference 13) would seem a "natural" for this service.

In this connection it is interesting to note that certain organic fluids, notably those having a large number of atoms per molecule have a temperature-entropy diagram with a positive slope to the vapor-mixture boundary (Reference 14). This means that isentropic expansion of the vapor phase of these fluids through the nozzles of fluidic devices would lead to a higher value of superheat in the vapor, rather than a lower value as in the case of water (Figure 11). The use of such a working fluid should help prevent

premature condensation of the fluid as it passes through the various fluidic elements in the system.

A representative fluidic power schedule is shown in Figure 12. This was prepared by cataloguing the active components in each attitude control subsystem in the Lunar Orbiter, and attempting a realistic estimate of the number of fluid amplifiers or other active fluid elements required to perform the same functions. A power nozzle size of 0.254 mm (0.010 in.) by 0.254 mm (0.010 in.) and an operating pressure of $6.88 \times 10^3$ N/m$^2$ (1.00 psig) were assumed for signal level components, giving a fluid power consumption of about 50 milliwatts each (Ref. 15). Where power amplifiers were indicated, 200 milliwatts each was assumed. Gyro power was based on current pneumatic aircraft gyros. The wide spread in the power estimate for the programmer is due to the difficulty in determining the number and type of fluidic components required for such a complex device, and in uncertainties as to practical implementation of certain functions, especially the memory section.

In general, the fluid power estimates are higher than the electrical power requirements for conventional electronic systems, but, if these systems were designed from the beginning for fluidic implementation, it is likely that the number of active components as well as the power requirements could be substantially reduced. It seems reasonable to assume that fluidic control systems would require essentially the same magnitude of power as their electronic equivalents.

## INTERFACE TRANSDUCERS

When both electronic and fluidic components are used in the same system, the problem of converting electrical signals to fluidic signals

(pressure or flow) and vice versa must be dealt with. The advanced state-of-the-art of miniature electrical pressure and flow measuring instruments offers a number of ready-made solutions to the fluidic-to-electrical interface, but the problem of simple and efficient electrical-to-fluidic signal conversion still awaits a practical solution.

The conversion device should have a size and weight consistent with the other fluidic elements in the system, and should preferably contain no moving parts and have no exotic requirements for the input voltage or current.

The use of ion drag pump principles for analog data (Reference 16), or spark discharge inputs for digital conversions (Reference 17) requires extremely high input voltages, while devices employing electric heaters to influence the flow of the working fluid in a manner similar to that of the previously described sun sensor (Figure 4b) require relatively high input power. Solenoid or piezoelectric actuated transducers (Reference 18) have more satisfactory electrical input requirements, but are generally more intricate in construction and involve moving parts.

Here, again, there are a number of workable approaches to the problem, but no really satisfactory hardware has yet been announced.

## CONCLUSIONS

With the possible exception of the star sensor, there do not appear to be any major problems in the development of fluidic equivalents for all the attitude control system components of Lunar Orbiter class spacecraft, although extensive development effort would be required in several areas. On the other hand, the incentives for developing a complete fluidic attitude control for this class of vehicle are not too strong at present. The inherently

high heat and radiation tolerance of fluidic components is, to a great extent, nullified by the necessary presence of other electronic systems in the vehicle, the most obvious being the telemeter.

Fluidic systems would appear to have a strong advantage in reliability, especially when competing with electromechanical components, because of the simplification and reduction in moving parts which can generally be achieved, but the question of reliability cannot be realistically explored until the development of flight oriented hardware has progressed much further than it has at present.

There are some situations in which fluidic devices are, by their very nature, best suited to the job at hand, and the thrust vector control seems to be one of these cases. This single subsystem appears to offer the greatest advantage to be derived from the application of fluidics to spacecraft control.

Fluidics (if the meaning of the word can be stretched to include gas lubricated bearings) also promises relief of some of the troublesome problems encountered in the IRU gyros.

Problems common to any application of fluidics to spacecraft control are those of fluid power supply and electro-fluidic interfaces. Although a start has been made in both these areas much remains to be done before flight qualified hardware can be built.

Figure 13 summarizes the current status and potential advantages of the components discussed in this paper.

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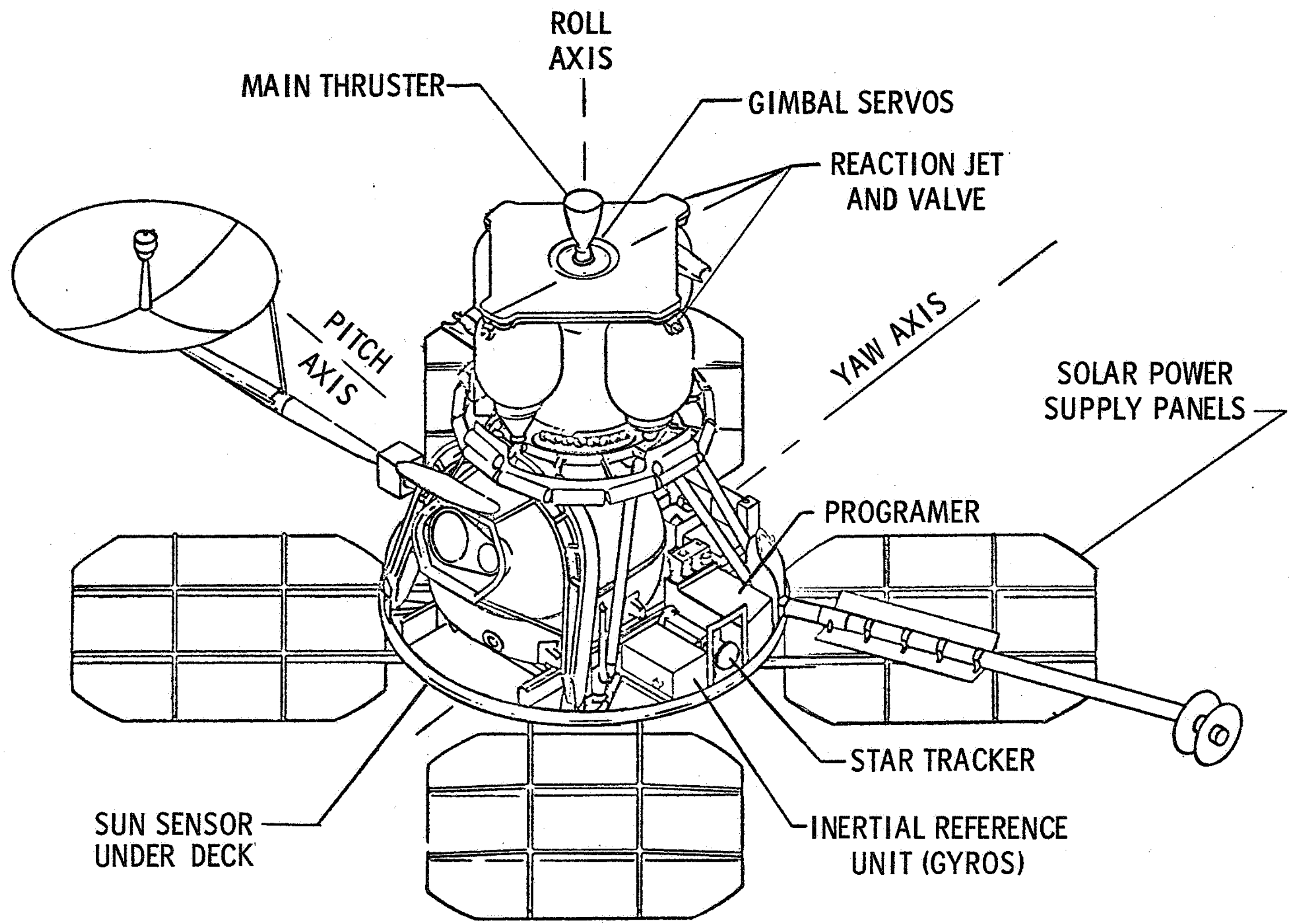


Figure 1.- Lunar Orbiter attitude control system.

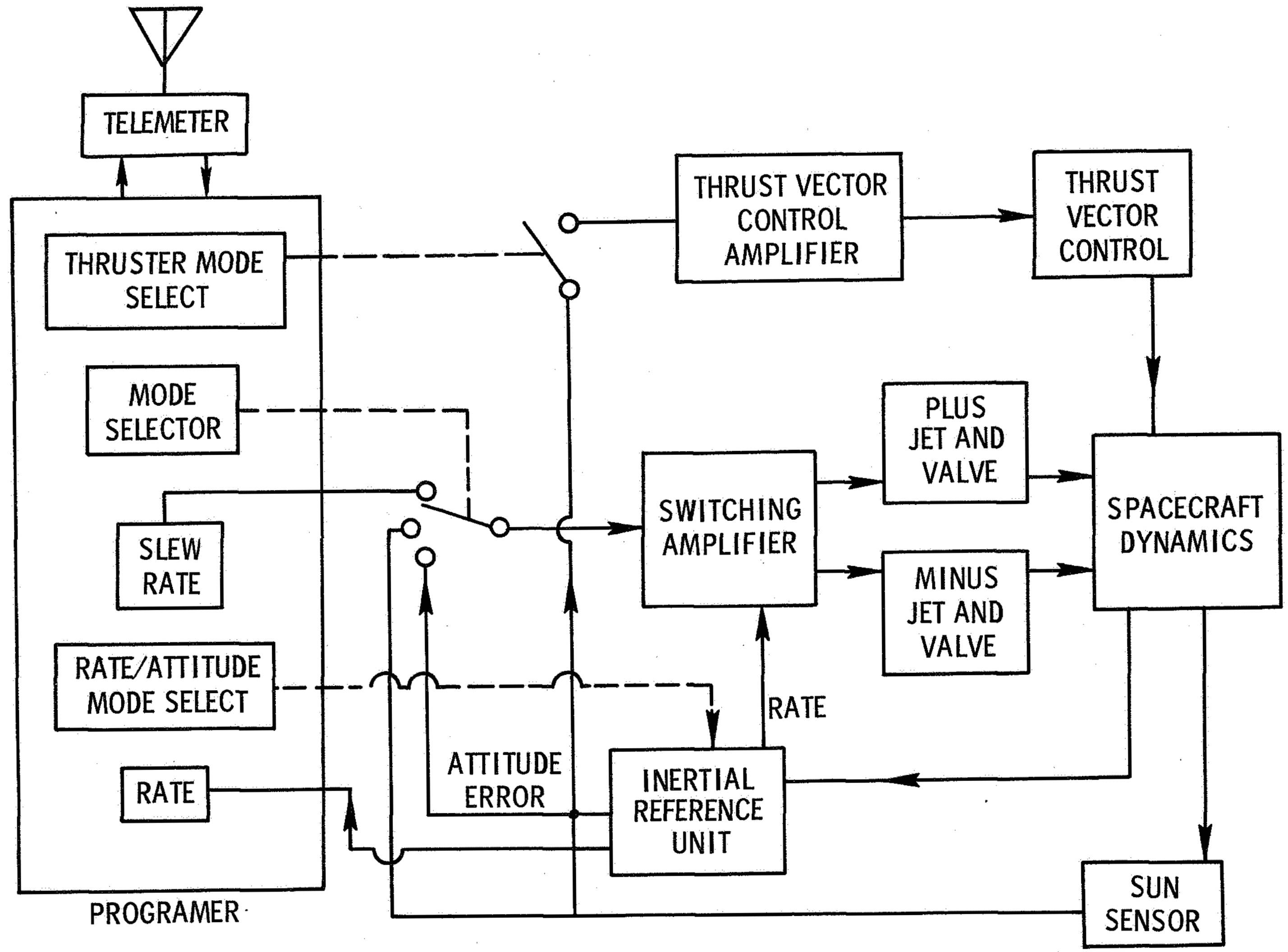


Figure 2.- Lunar Orbiter pitch and yaw channel.

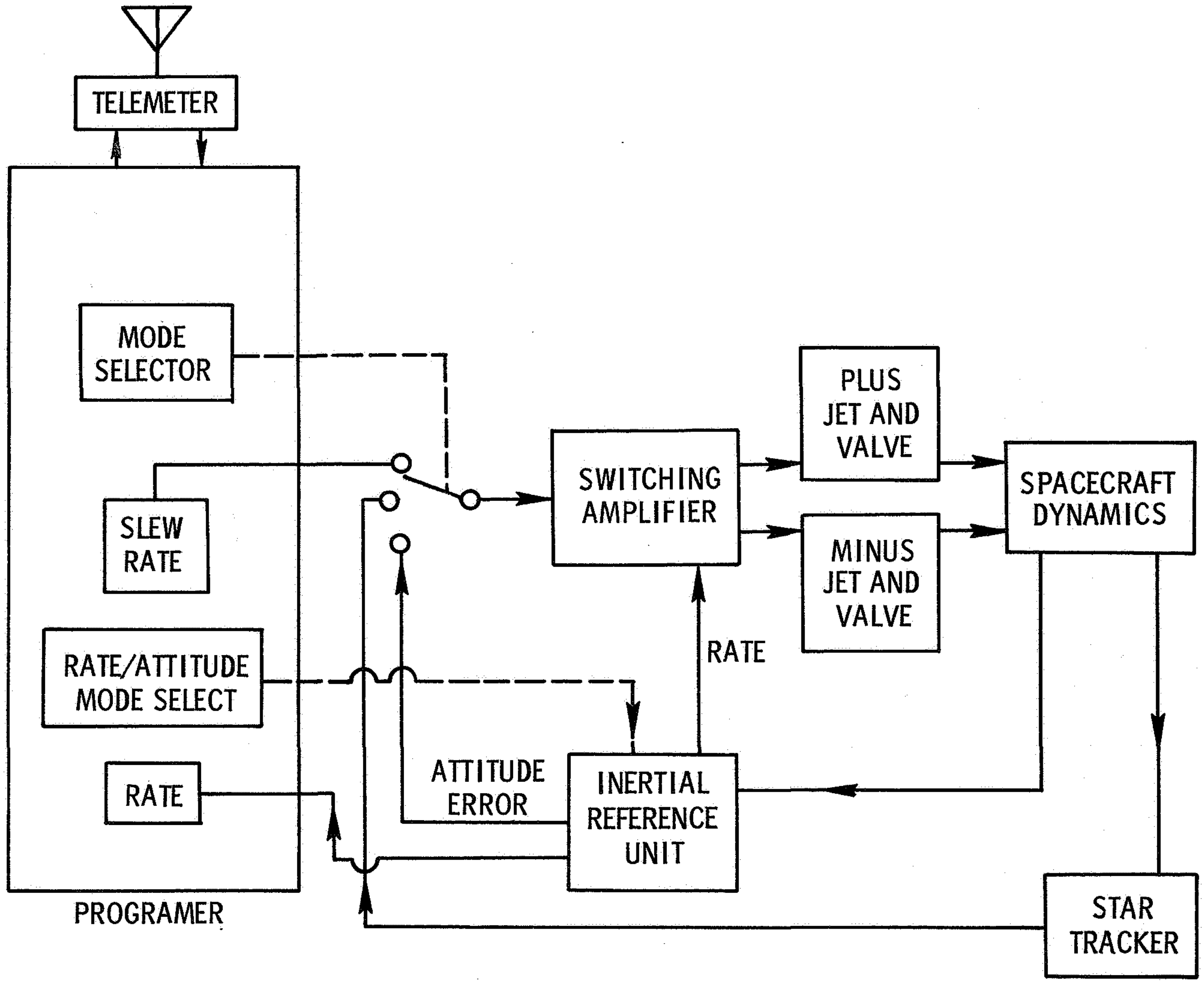


Figure 3.- Lunar Orbiter roll channel.

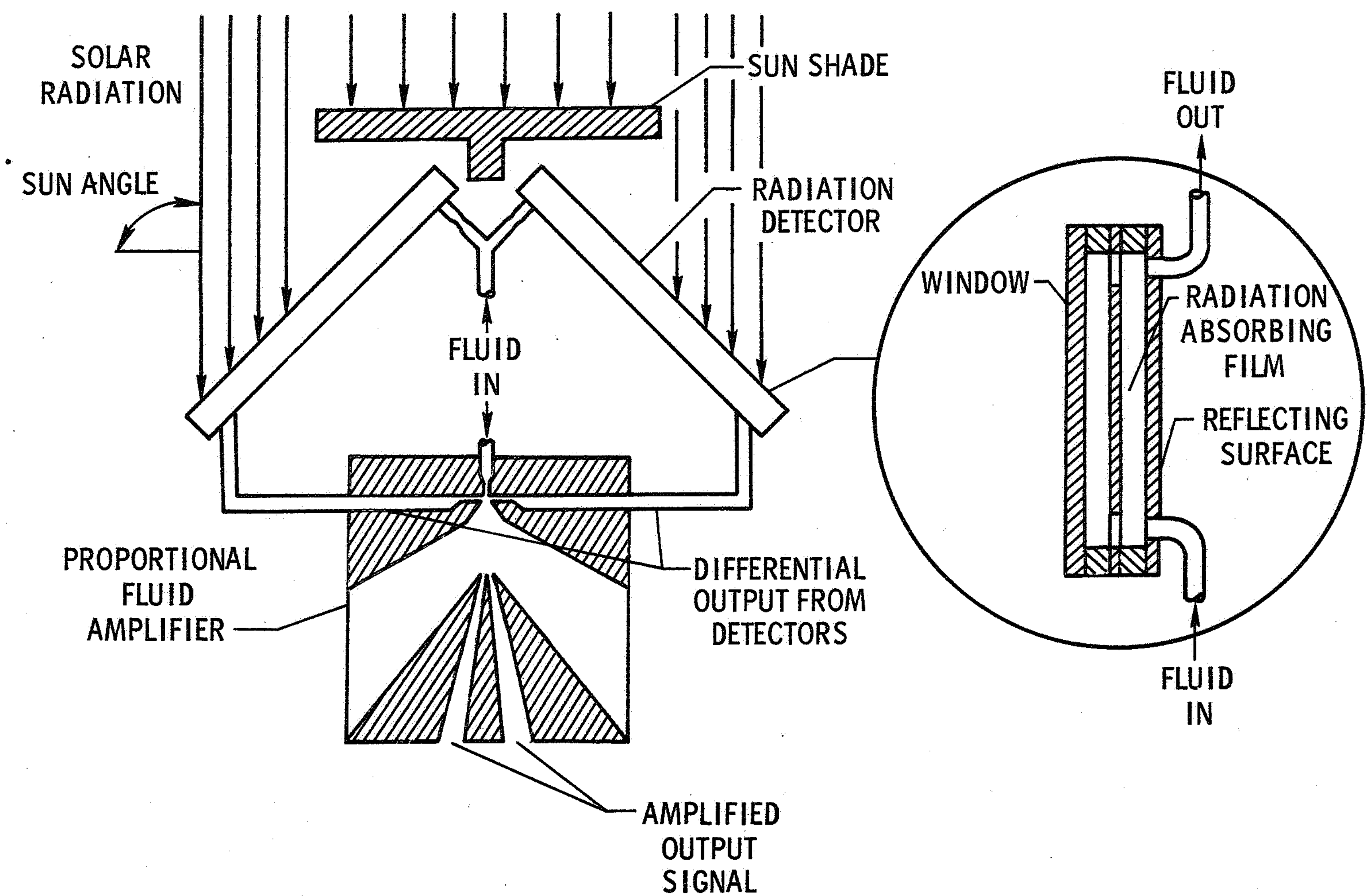


Figure 4.- Pure fluid sun sensor.

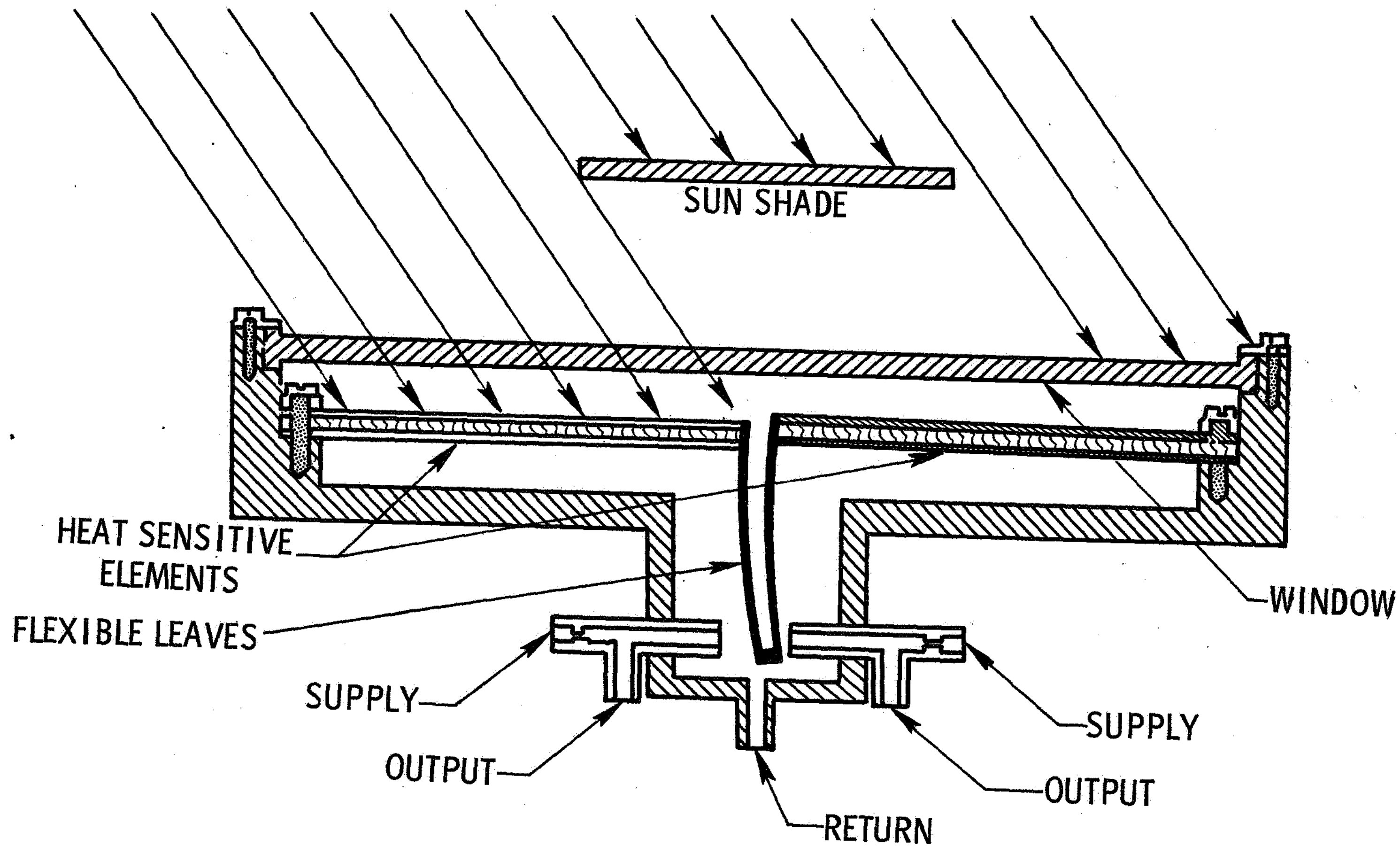


Figure 5.- Sun sensor.

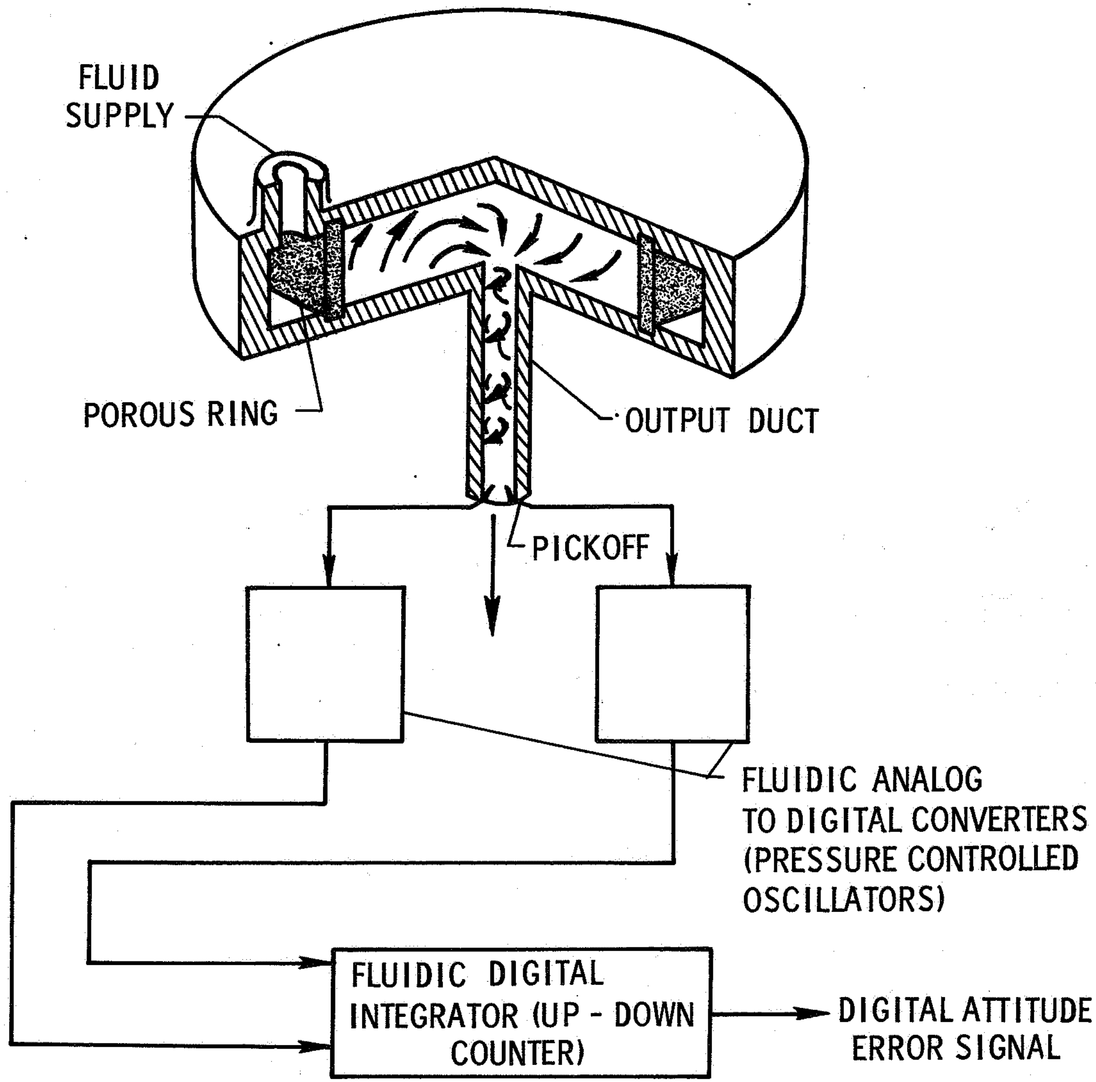


Figure 6.- Vortex rate sensor attitude reference.

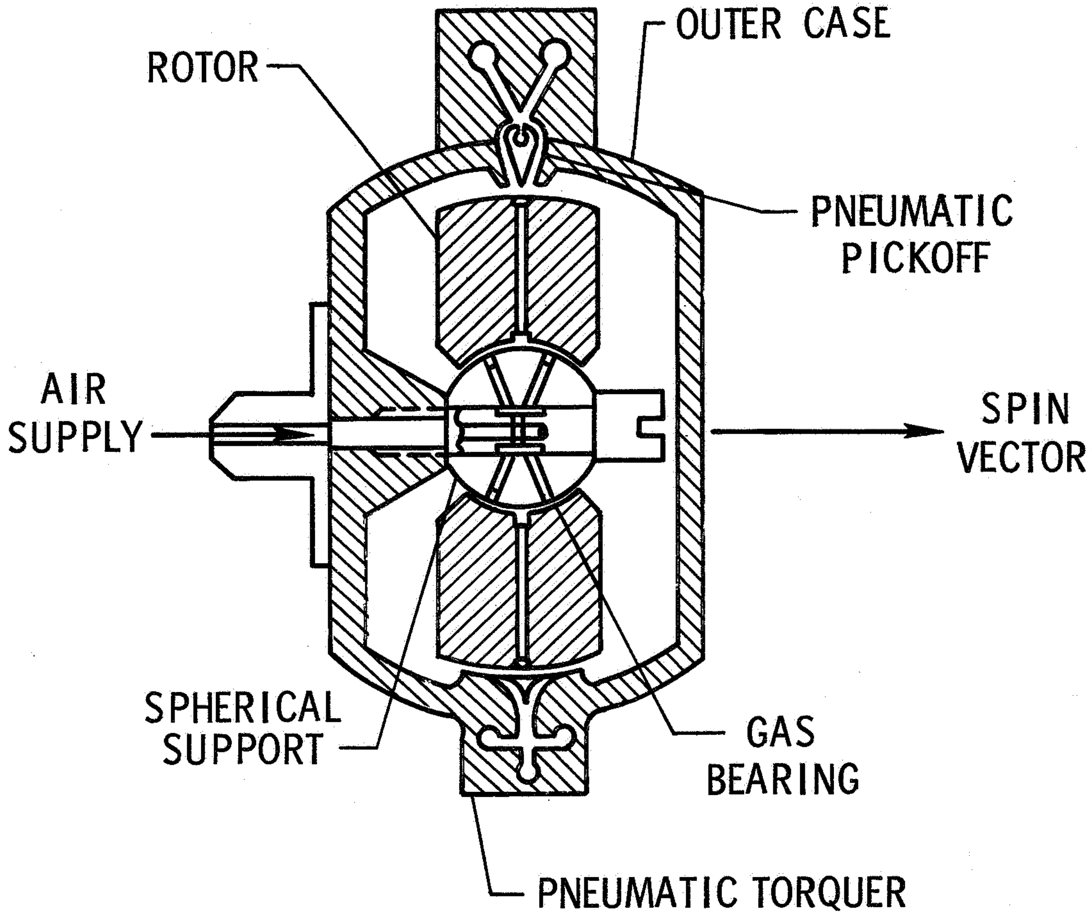


Figure 7.- Fluidic gyroscope attitude reference.

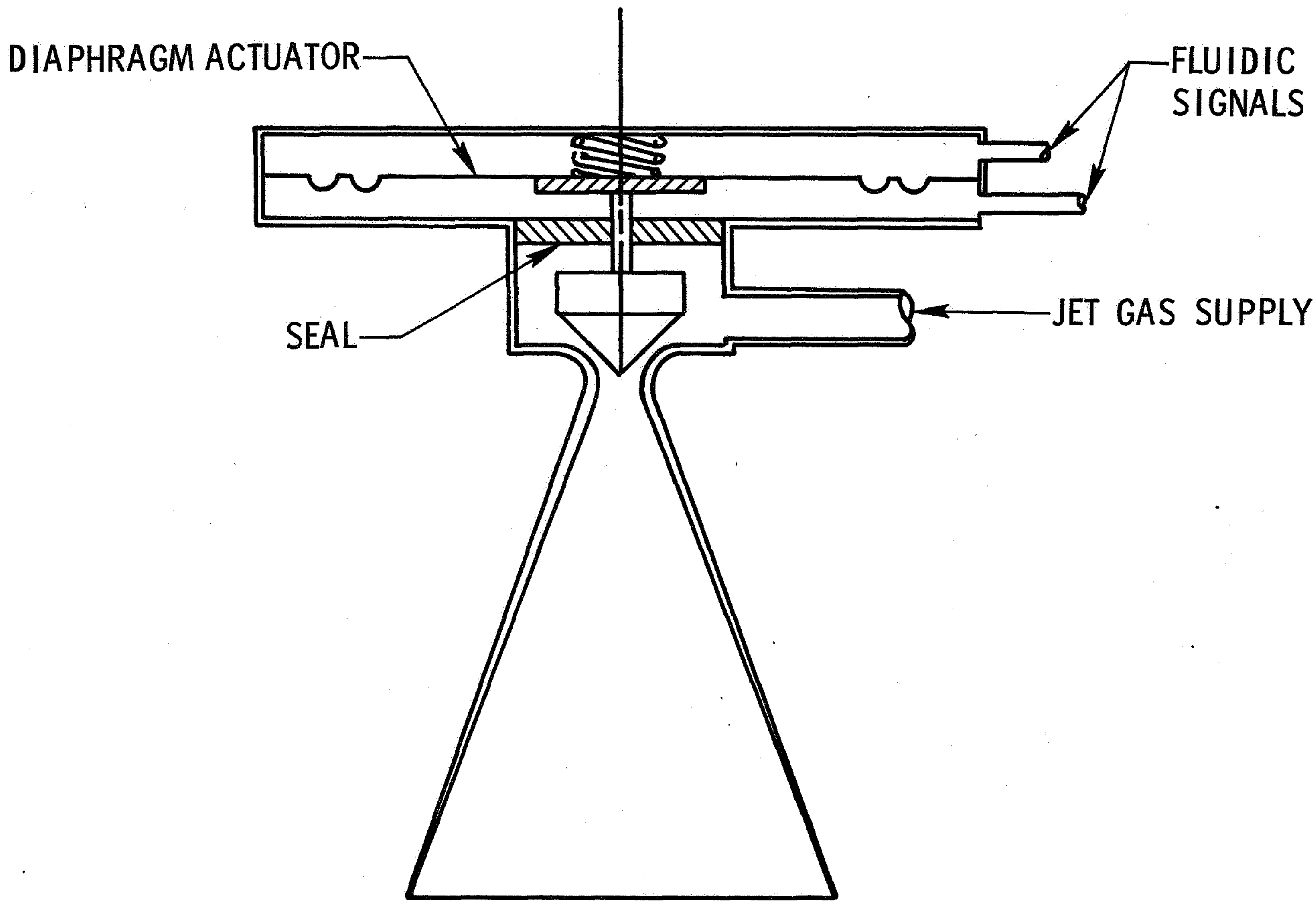


Figure 8.- Reaction jet valve.

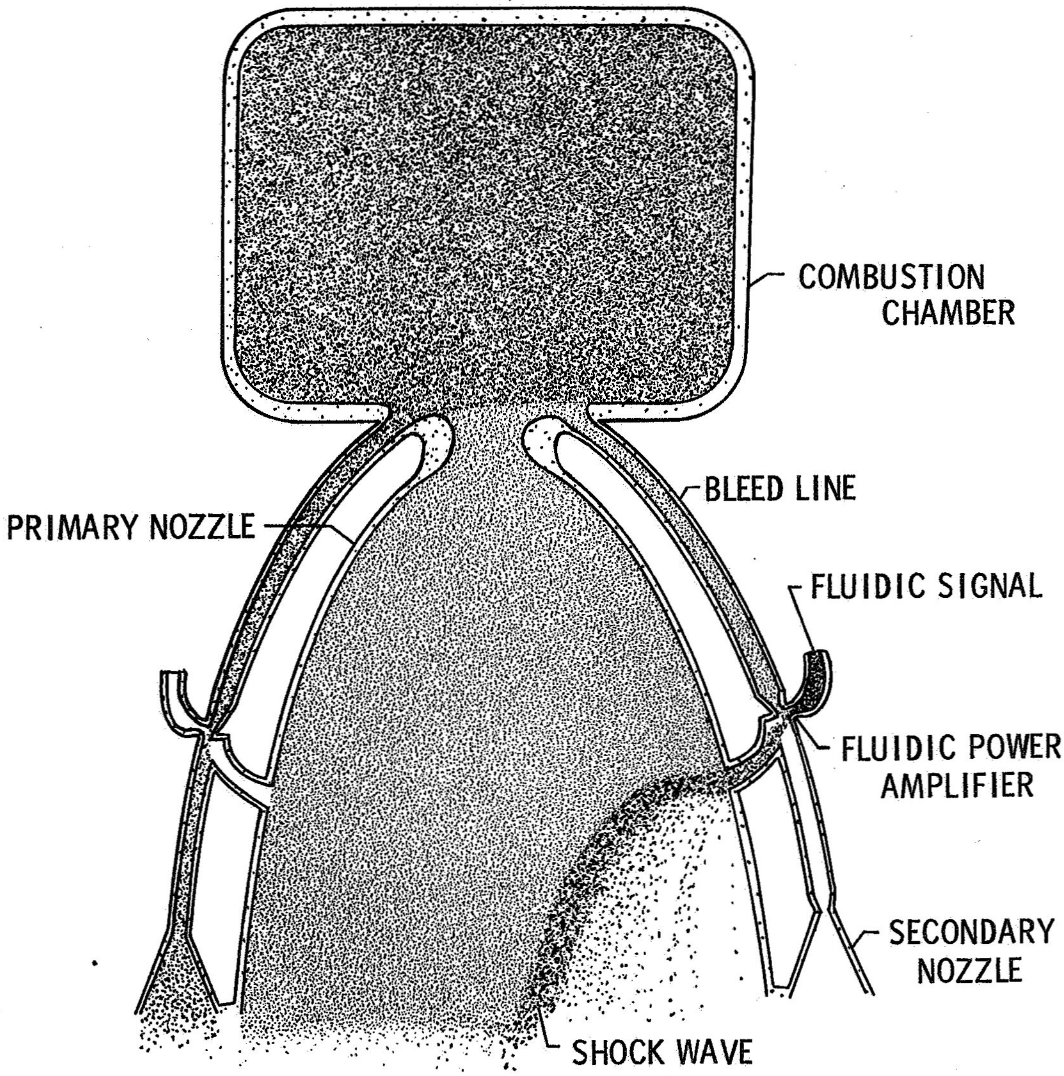


Figure 9.- Fluidic secondary injection thrust vector control.

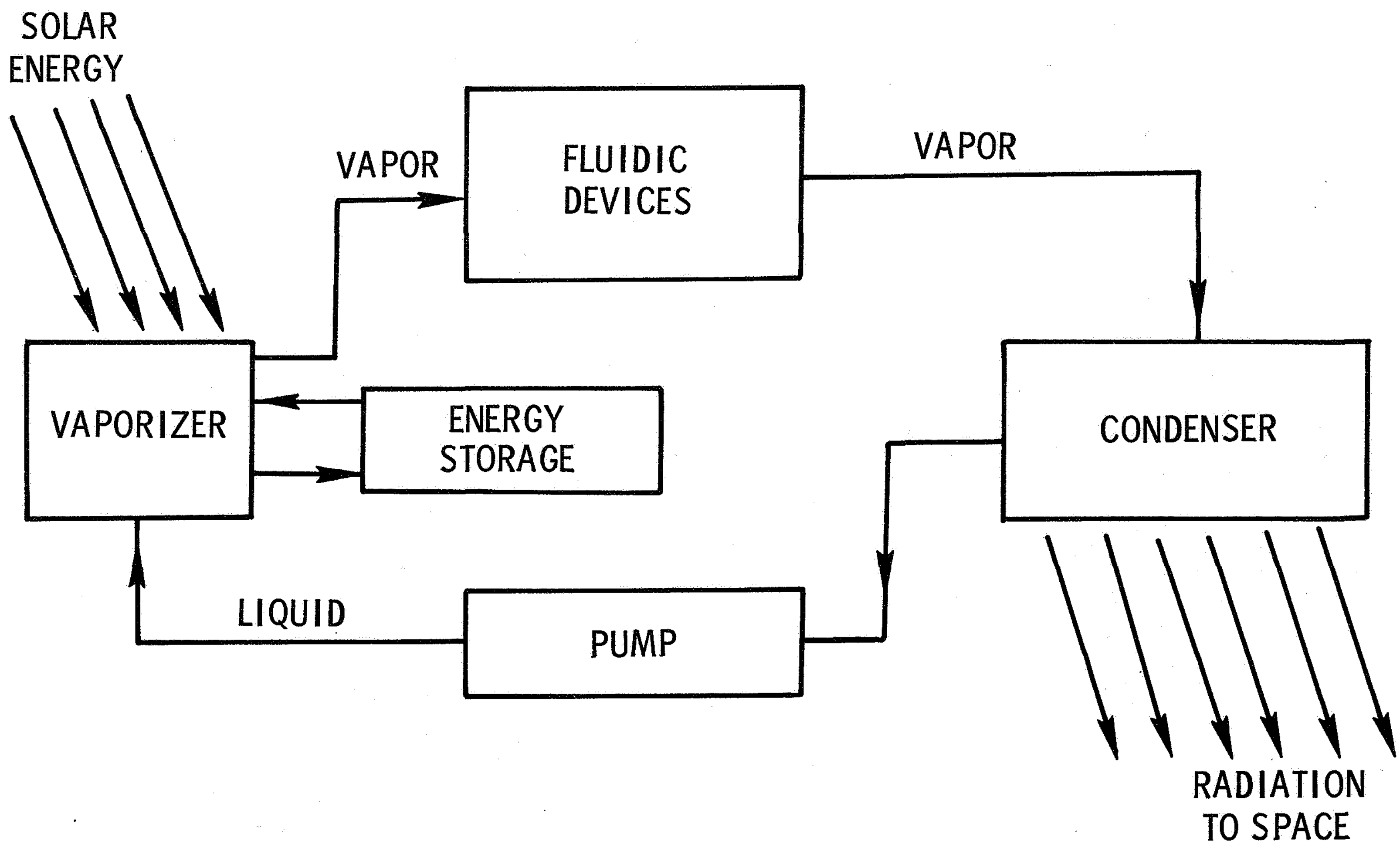


Figure 10.- Rankine cycle fluid power supply.

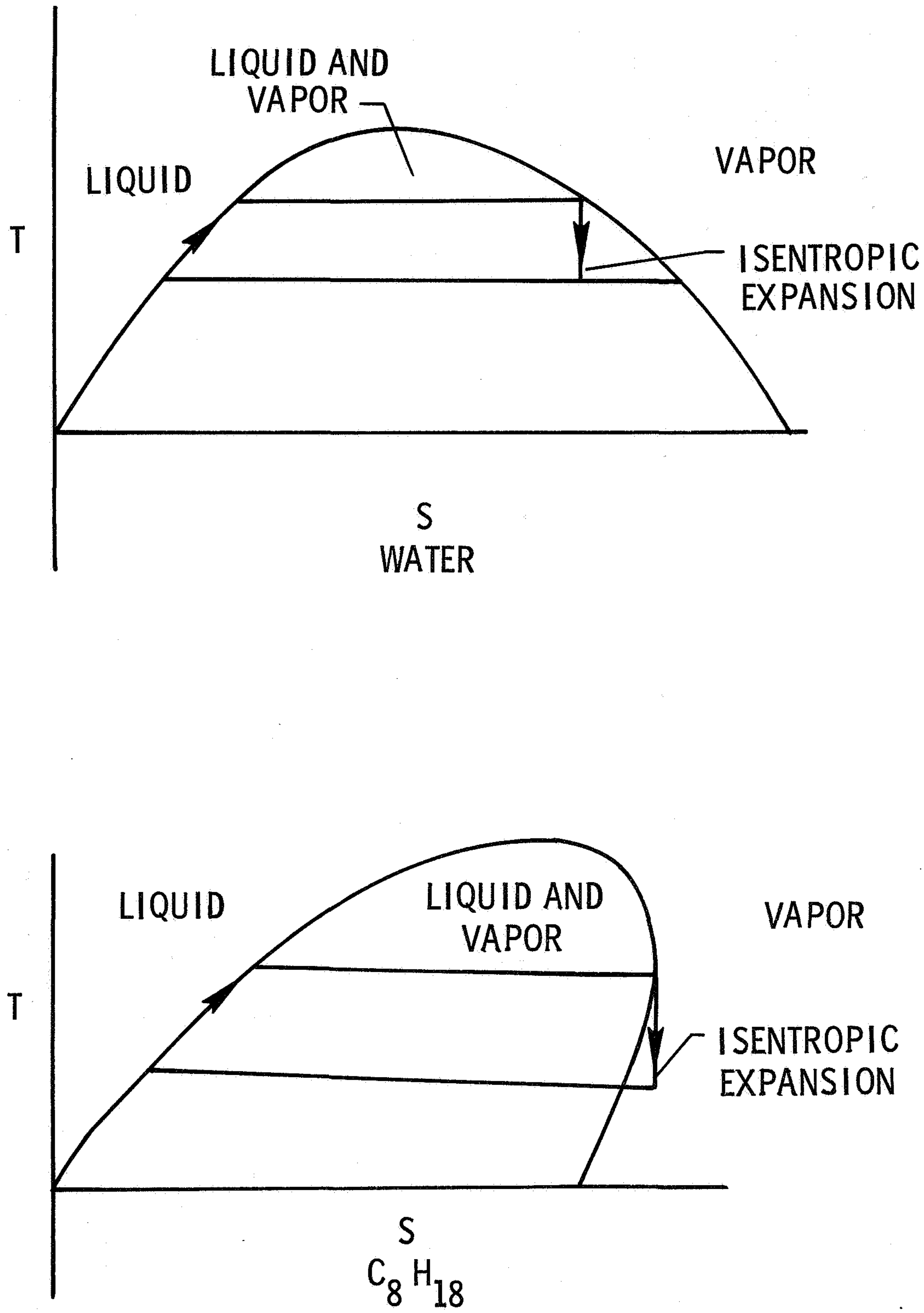


Figure 11.- Working fluid temperature entropy diagrams.

| | POWER, WATTS | | ACTIVE COMPONENTS | |
|---|---|---|---|---|
| | LUNAR ORBITER | FLUIDIC EQUIVALENT | LUNAR ORBITER (TRANSISTORS) | FLUIDIC EQUIVALENT (FLUID AMPLIFIERS) |
| PROGRAMER | 16 | 27 TO 110 | 289 | 350 TO 1300 |
| CONTROL AMPLIFIERS | 2.1 | 12.5 | 305 | 170 |
| SUN SENSORS | 0 | 0.5 | 0 | 4 |
| STAR SENSOR | 5.3 | 2 | 65 | 20 |
| GYROS | (3 GYROS) 12 | (2 GYROS) 10 | 132 | 6 |
| THRUST VECTOR CONTROL | 173 | 600 | 16 | 8 |

Figure 12.- Power and component comparison.

| ITEM | CURRENT STATUS | ADVANTAGES |
| --- | --- | --- |
| PROGRAMER | ALL NECESSARY COMPONENTS DEVELOPED | HIGH ENVIRONMENTAL TOLERANCE |
| CONTROL AMPLIFIERS | ALL NECESSARY COMPONENTS DEVELOPED | HIGH ENVIRONMENTAL TOLERANCE |
| SUN SENSORS | LAB MODELS TESTED | HIGH ENVIRONMENTAL TOLERANCE |
| INERTIAL REFERENCE UNIT (GYROS) | VORTEX RATE SENSORS: REQUIRED THRESHOLD BEYOND THE STATE OF THE ART<br>GAS BEARING GYROS: FLIGHT QUALIFIED | SIMPLICITY, LONG PREDICTABLE LIFE, NO TEMPERATURE CONTROL REQUIRED, EASE OF STERILIZATION |
| JET VALVES | PURE FLUID VALVES: PROBABLY NOT FEASIBLE<br>MECHANICAL VALVES: WELL WITHIN THE STATE OF THE ART | FASTER RESPONSE |
| TVC UNIT | WITHIN STATE OF THE ART: REQUIRES EXTENSIVE HARDWARE DEVELOPMENT | SIMPLICITY, NO MOVING PARTS AND WEIGHT REDUCTION |
| POWER SUPPLY | REQUIRES EXTENSIVE DEVELOPMENT | NONE (REQUIRED FOR ANY FLUIDIC ATTITUDE CONTROL SYSTEM) |
| INTERFACE TRANSDUCERS | REQUIRES EXTENSIVE DEVELOPMENT | NONE (REQUIRED FOR ANY FLUIDIC ATTITUDE CONTROL SYSTEM) |
| STAR TRACKER | PROBABLY NOT FEASIBLE | NONE |

Figure 13.- Status chart.